Radiation studies for MU2E-II

S. E. Müller

Helmholtz-Zentrum Dresden-Rossendorf

MU2E-II Workshop,
February 22, 2022

Working group on Radiation

Conveners:

- Michael MacKenzie (Offline)
- Stefan Müller (FLUKA)
- Vitaly Pronskikh (MARS15)

Additional Contributors:

- Anna Ferrari, Reuven Rachamin, Vadim Kashikin, James Popp, David Pushka

Liaison to other WGs:

- Yuri Oksuzian (CRV), Sophie Middleton (Sensitivity), Giani Pezullo (TDAQ), Mete Yucel (Tracker)

Mailing list:

- <mu2eii-radiation@listserv.fnal.gov>

Scope of the WG

The task of the WG was "`to deal with the radiation issues and possible mitigations, both for the accelerator (and site safety) and the detector`".

To fully do this for MU2E-II design parameters would require a large computing campaign (and ideally a near-finalized design).

The idea was thus to try to extrapolate the MARS15 simulations for the 8-GeV beam of MU2E to the 800 MeV - 100 kW proton beam of MU2E-II.

In addition, we performed simulations around the production target using both tungsten and carbon as target material and compared the results between the codes.

As these simulations go beyond pure radiation studies, it turned out that they would better fit in other sections of the White Paper.

Status of the “Radiation”-Section - Tools

‘‘Tools’’ section describing the simulation codes currently first subsection of ‘‘Radiation’’ section, but maybe should go to appendix? (Geant4 part still to be written...)

V. RADIATION

A. Tools

1. *FLUKA*

The FLUKA [101–103] radiation transport and interaction code is a fully integrated particle physics Monte Carlo simulation package containing implementations of sound and modern physical models. FLUKA simulates the interaction and transport of 60 different particles, and also allows to estimate residual radiation and activation. Editable `FORTRAN` routines allow to include user-defined settings and modifications. A powerful graphical interface [104] facilitates the editing of FLUKA input, execution of the code and visualization of the output. The Mu2e magnetic field maps have been also interfaced to FLUKA and allow a realistic modeling of the trajectories of charged particles.

2. *MARS15*

The MARS15 code [105, 106] is a fully integrated particle transport and interaction code consisting of a set of Monte Carlo programs (written in Fortran and C++) that allow modeling and simulation of interactions of all kinds of leptons, hadrons, photons, and heavy ions with matter. Interactions in the energy range spanning from a fraction of electronvolt up to hundreds of TeV can be simulated. Model geometry can be described in several ways including a built-in extended geometry description language, ROOT geometry, and the import of external gdml files. MARS15 incorporated CEM and LAQGSM [107] generators for the description of particle-nuclei and particle-particle interactions above 100 MeV. Also, MARS15 includes the DeTra [108] code to model nuclear decays and transmutations as well as EGS5 [109] code to model low-energy electromagnetic showers.

3. *GEANT4*

to be written

HZDR

Radiation at FERMILAB site

Prompt dose above PS and DS hatches extrapolated from MU2E simulations using dose $\propto E_p^{0.8}$.

B. Radiation environment

1. *Fermilab site*

An important aspect of the shielding assessment is the determination of the prompt dose above PS and DS hatches. By now, explicit MARS15 simulations have been made for the 8-GeV beam of the baseline Mu2e. In order to estimate the projected prompt dose above the berm (above the PS Hall) at the 800-MeV 100-kW proton beam of PIP-II by the order of magnitude, the following assumptions have been made: the proton beam intensity at Mu2e-II was taken to be 7.8E14 p/s; based on previous experience at Fermilab, we supposed that the prompt dose $\propto E_p^{0.8}$ (E_p – primary proton beam energy). In the case of the residual dose, we made a similar presupposition regarding the energy dependence to scale the Mu2e baseline dose to the Mu2e-II one. In the baseline Mu2e, some typical radiation quantities were calculated as follows: 1) the residual dose in air 1 foot away from the West wall in the PS hall will be $\sim$ 300 mrem/hr [110] (expected to be $\sim$ 6.2 Rem/hr in Mu2e-II based on the assumptions discussed above); 2) the peak prompt dose above the berm (PS Hall area) will be 10 mrem/hr in baseline Mu2e [111] (206 mrem/hr in Mu2e-II); the prompt dose above the berm away from the peak ($\sim$ 4 meters South) will be $\sim$ 0.01 mrem/hr in Mu2e [111] ($\sim$ 0.2 mrem/hr in Mu2e-II).

add thoughts on possible mitigation of problematic doses?

Radiation around Target

The radiation around the target has been studied in `PoS ICHEP2016 (2017) 257` for different MU2E-II proton beam energies.

2. Around target

The SC coils of the PS will be experiencing a higher radiation load; therefore, a simulation study has been undertaken to assess their energy deposition and DPA damage under the Mu2e-II conditions (see [112] for details). In the proton energy range of interest for the muon program at Fermilab (0.5 – 8 GeV) and for the current Mu2e apparatus design, DPA damage and peak power density are maximal in the 2-4 GeV range. It is assumed that the coil determines the constraints and are characteristic of the Mu2e magnet technology under consideration. The maximum of the muon stopping rate is in the range from 2 to 3 GeV. The figure of merit (FOM) is defined here as the ratio of the number of muon stops in the stopping target to the DPA rate in the hottest spot of the PS coil; the maximum of this quantity lies between 1 and 3 GeV (FOM for 0.8 GeV is close to that of 1 GeV and is close or slightly better than FOM at 8 GeV (Mu2e baseline).

The DPA constraint was determined to be at the level of 4E-5 DPA/yr; that level would allow to run the experiment without shutdown for annealing for about a year. In the case of the bronze HRS with the inner bore radius of 20 cm, the baseline coil design at an 800-MeV PIP-II proton beam would tolerate a 10-kW beampower; for the tungsten HRS, this beampower would be 40 kW. However, if one increases the inner bore radius to 25 cm, the tolerable beampower for the tungsten HRS would be higher than 100 kW.

Radiation at detector and res. MU2E radiation

The radiation in the DS hall locations has been extrapolated in the same way as for the PS radiation estimates.

C. At detector locations

The prompt dose in the DS Hall's two important locations for Mu2e baseline are 10 mrem/hr (equipment alcove) and 6 mrem/hr (electronics alcove) [113]. After aforementioned corrections for the beam energy and beam intensity, the estimated doses for the Mu2e-II conditions are $\sim$ 206 mrem/hr (equipment alcove) and $\sim$ 125 mrem/hr (electronics alcove), respectively. Importantly, the latter numbers are only tentative estimates made under many assumptions including that the Mu2e-II Target Station and the entire facility would be exactly the same as Mu2e baseline.

The part on residual MU2E radiation still needs to be written.

D. Residual Mu2e radiation and access for Mu2e-II construction

to be written

S. E. Müller | HZDR | http//www.hzdr.de

Simulation studies in "Target design" section

The conveyor target design has been modeled with MARS15, FLU-KA and GEANT4. This is partially mentioned in the "Target design" section:

To cross check and compare results obtained with other Monte Carlo codes, two target designs for Mu2e-II have been modeled with FLUKA and MARS15:

- a target made out of 28 carbon spheres (0.75 cm radius)
- a target consisting of 11 tungsten spheres (0.5 cm radius)

For both target designs, the surrounding HRS and PS structures have been included based on the Mu2e geometry (the HRS inner bore was enlarged to 25cm radius to accommodate the tungsten target design). The total number of the spherical elements in the HRS inner bore in the simulations was about 285.

Figures 12 and 13 show the FLUKA geometrical models for both target designs. Figure 14 shows the proton fluence obtained with FLUKA for a 800 MeV proton beam hitting the carbon target. It can be noted how the location of the carbon spheres follows the proton trajectories in the magnetic field in order to maximize the resulting particle yield.

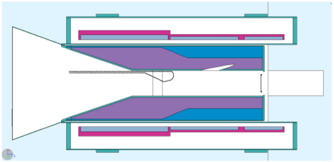


FIG. 12. FLUKA geometrical model of the tungsten target design inside the HRS and PS sturctures.

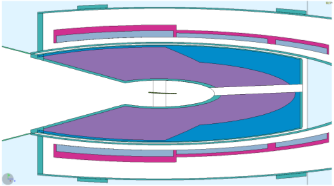


FIG. 13. FLUKA geometrical model of the carbon target design as seen in the plane of deflection of protons in the magnetic field.

Simulation studies in “Target design” section

The conveyor target design has been modeled with MARS15, FLUKA and GEANT4. This is partially mentioned in the “Target design” section:

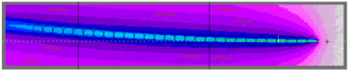


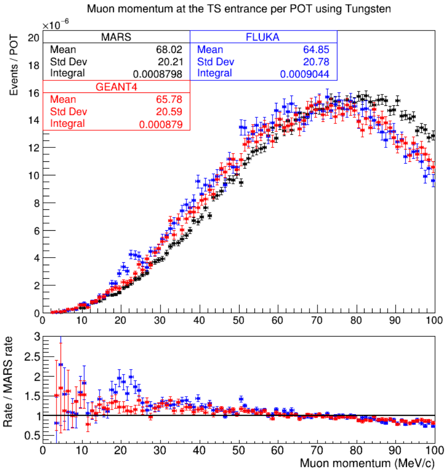
FIG. 14. Proton fluence obtained with FLUKA for 800 MeV proton beam hitting the carbon target.

While the current FLUKA implementation of the target designs and the surrounding HRS and PS structures allows to estimate the radiation in the vicinity of the PS region, work is underway to include additional geometry structures with the goal to perform a global shielding and radiation analysis with FLUKA and compare with the results obtained with MARS15.

Particle yields at entrance to TS1

We started to compare particle yields at the entrance to TS1 with FLUKA, GEANT4 and MARS.

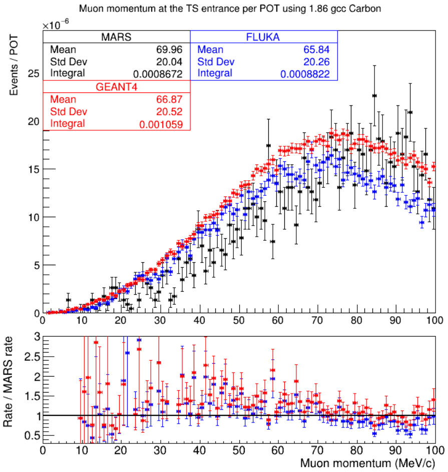
μ^- per POT for tungsten conveyor target:



Particle yields at entrance to TS1

We started to compare particle yields at the entrance to TS1 with FLUKA, GEANT4 and MARS.

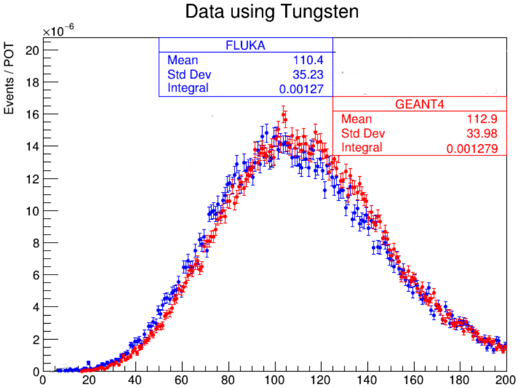
μ^- per POT for carbon conveyor target:



Particle yields at entrance to TS1

We started to compare particle yields at the entrance to TS1 with FLUKA, GEANT4 and MARS.

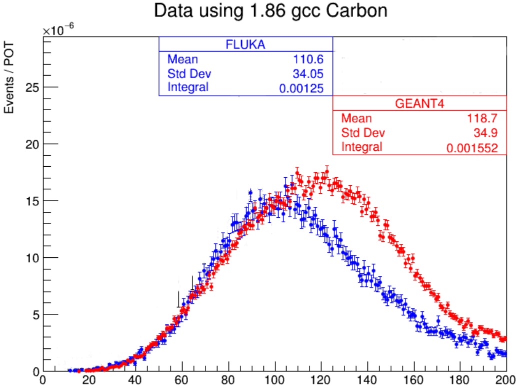
π^- per POT for tungsten conveyor target:



Particle yields at entrance to TS1

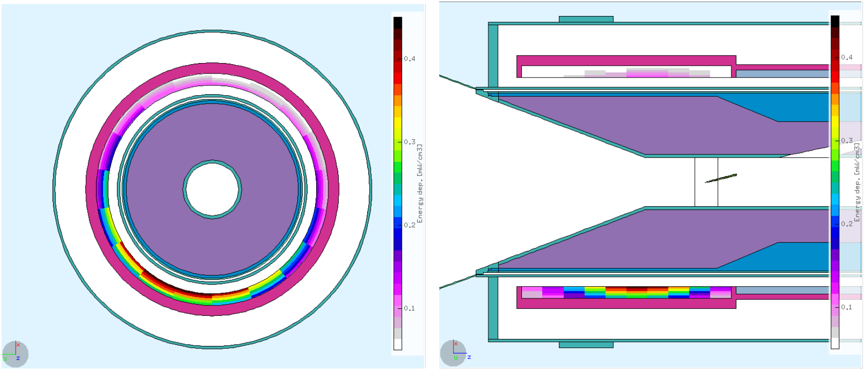
We started to compare particle yields at the entrance to TS1 with FLUKA, GEANT4 and MARS.

π^- per POT for carbon conveyor target:



Energy deposition in PS coils with FLUKA

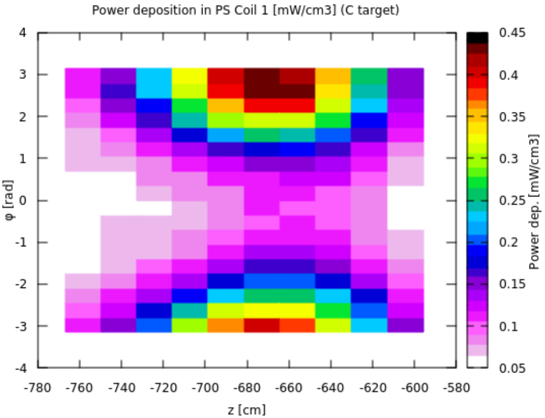
I started to look at the energy deposition in coil 1 of the PS (which is the most exposed).



Carbon target design

Energy deposition in PS coils with FLUKA

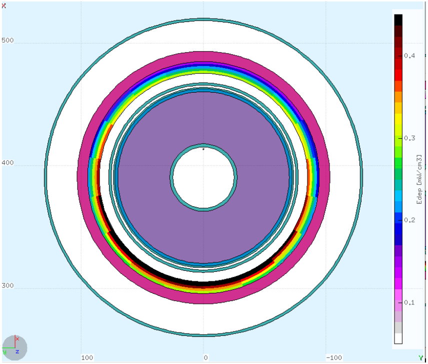
I started to look at the energy deposition in coil 1 of the PS (which is the most exposed).

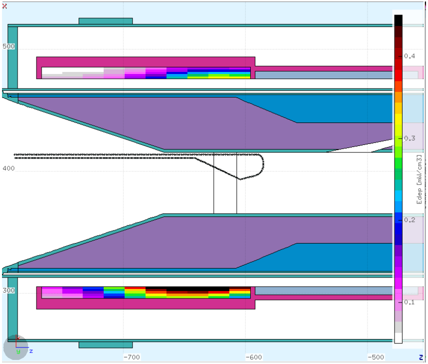


Carbon target design

Energy deposition in PS coils with FLUKA

I started to look at the energy deposition in coil 1 of the PS (which is the most exposed).

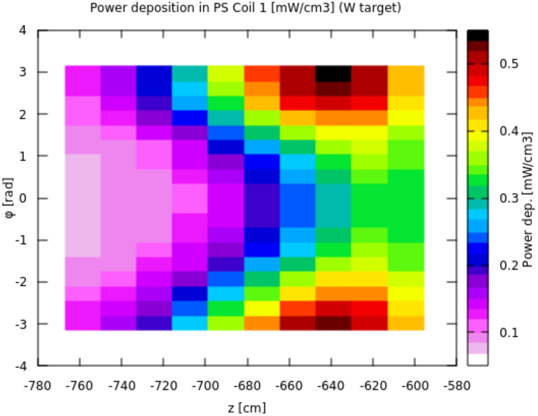




Tungsten target design

Energy deposition in PS coils with FLUKA

I started to look at the energy deposition in coil 1 of the PS (which is the most exposed).



Tungsten target design